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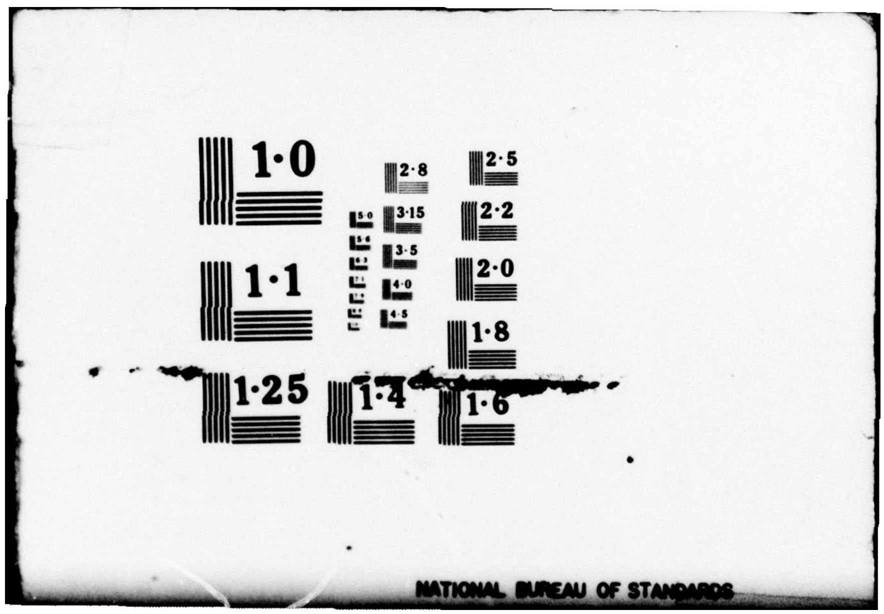
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X-RAY FLARE AND SHORT-WAVE FADE DURATION MODEL.

Outage time is directly related to solar peak of X-ray event by use of event rise characteristics.

(10) P.E. Argo, I.J. Rothmuller [redacted] J.R. Hill

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ADMINISTRATIVE INFORMATION

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A model is developed for predicting, in real time, the time-to-recovery for hf signals during a solar X-ray event. The model is designed to give predictions as early in the event as possible, and is backed by an update scheme to correct inaccurate predictions when such are recognized. The model was made possible by the fact that the recovery period of most solar X-ray events can be characterized by an exponential decay with one of four time constants. The choice of time constant can be made by using observations of the rise portion of the event.

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OBJECTIVE

Develop a method for predicting short-wave fade (SWF) outage times due to solar X-ray events. The prediction should be available early in the event.

RESULTS

The outage time of SWF events may be directly related to the solar peak of the X-ray event by use of event rise characteristics. The decay slope can be accurately depicted as having one of four exponential time constants, the constant chosen by the value of the ratio of the flux change to the rise time. Since this is available as soon as a peak is recognized, the modeled decays then allow quick assessment of the impact of the event on communication systems.

RECOMMENDATIONS

1. Adopt the SWF duration model presented in this report.

2. Investigate the utility of applying the X-ray burst decay model to vlf sudden phase anomaly (SPA) events.

INTRODUCTION

Solar X-ray flares may cause complete blackouts of the hf spectrum for varying periods of time; therefore, a method of predicting the short-wave fade (SWF) outage duration as a function of hf frequency has been developed. The concept is to give a communications officer a curve of recovery time (in real time) as a function of frequency, so that he can allocate his resources for maximum effectiveness. The information is displayed to emphasize the shorter time vulnerabilities of the higher frequencies. This format may help motivate members of the communication community to use frequencies above the lowest satisfactory one, as they notice the quicker recovery of the higher frequencies.

The present model is predicated upon the relationship between the lowest observable frequency (LOF) and the X-ray flux emitted by a solar flare. A detailed physical description of this relationship has been given previously (ref 1). An accurate empirical relationship was also developed relating X-ray flux to LOF (ref 2). The formulation will be used in this model.

A stumbling block for time-to-recovery predictions during X-ray events has been the modeling of the flare recovery itself. We noticed that one of two exponential decay curves would describe the recovery of many events, and, even more important, that the decay constant can be related to the rise characteristics of the X-ray event. In refining the present model, we have added two more decay curves in order to extend the model's usefulness to cover almost every event. The model also includes an event detection routine that looks for emergence above the background flux. The progress of the flare recovery is monitored continuously in a correction routine that updates the decay slope prediction whenever the difference between the predicted and actual X-ray fluxes exceeds an established tolerance level.

X-RAY FLARE MODEL

A solar X-ray event can be described as a steep rising portion peaking out and followed by a less steep recovery (decay) back to pre-event conditions. Much effort has been put into characterizing these events by "simple" forms (MB Bleiweiss, private communication) but these in general have failed to accurately describe flare behavior. In our investigation we noticed that the recovery portions of many events can be described by one of two exponential decay curves (time constants τ_1 = 10.2 min, τ_2 = 45.0 min). In fact, the steeper decay curve turns out usually to include the longer time constant term with an amplitude of ~0.1 of the peak flux; see figure 1 (ie, flux = 0.9 * peak * e^{-t/τ_1} + 0.1 * peak * e^{-t/τ_2}).

[1]NELC TR 1840, Solar X-Ray Spectrum Definition and the Prediction of Ionospheric Radio Wave Propagation, MP Bleiweiss, September 1972

[2]NELC TR 1938, Sudden Ionospheric Disturbance Grid, RB Rose and others, December 1974

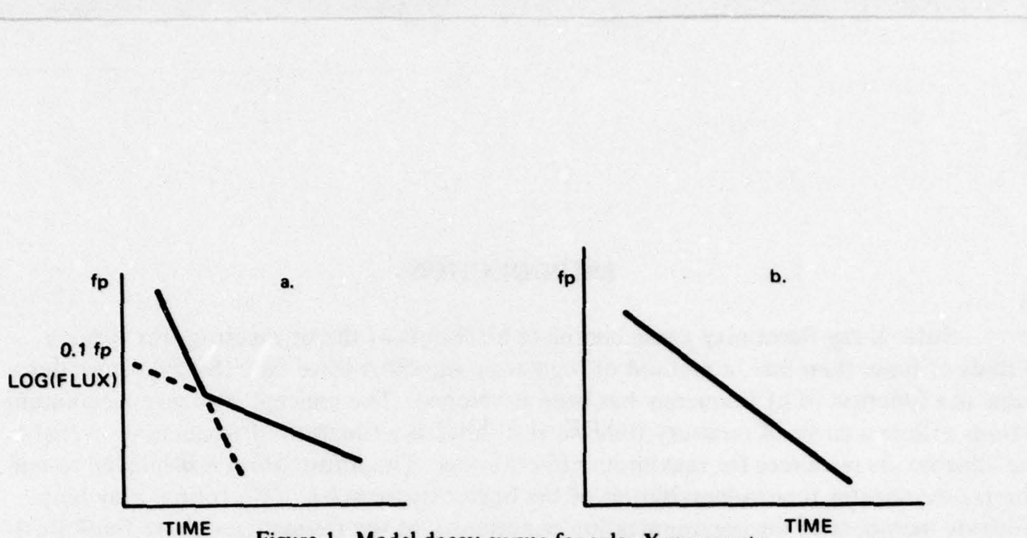

Figure 1. Model decay curves for solar X-ray events.

At the same time it became evident that the rise slopes of events with the short recovery time constant were "steeper" than those of events with the long recovery time constant. This is important because the sooner the prediction can be made, the greater the usefulness of event duration predictions, and this scheme allows predictions at the event peak. The rise portion of the events is most effectively characterized as a ratio in the form:

$$r = \frac{\log_{10} \dfrac{\text{peak flux}}{\text{pre-event flux}}}{\text{rise time}} \tag{1}$$

In the implementation of the model we found the method less susceptible to rise time determination problems if we replaced the peak flux by "pre-event flux +90% flux change" and the pre-event flux by "pre-event flux +40% flux change." The "flux change" is the difference between the peak flux and the pre-event flux.

In a more comprehensive examination of the available Solrad 9 X-ray data (1–8Å) (0.1–0.8 nm) (>100 events) we derived a more complete flare model, containing four decay slopes. The additional two are much steeper (τ_3 = 5.2 min, τ_4 = 2.2 min) and follow the original pattern of steep rise followed by steep decay. Actually, these two very steep decays tend to create very short events, and interestingly enough these events usually are of significantly lower amplitude than the two longer decay constant events. Again, these short events are a combination of two slopes, as in figure 1a.

The X-ray recovery model can be described by four simple equations, characterized by the modified flux change to rise time ratio (r'):

$$\text{flux} = 0.9\, f_{peak}\, e^{-t/2.2} + 0.1\, f_{peak}\, e^{-t/5.2} \qquad r' > 1.5 \tag{2a}$$

$$\text{flux} = 0.9\, f_{peak}\, e^{-t/5.2} + 0.1\, f_{peak}\, e^{-t/10.2} \qquad 1.5 > r' > 0.64 \tag{2b}$$

$$\text{flux} = 0.9\, f_{peak}\, e^{-t/10.2} + 0.1\, f_{peak}\, e^{-t/45.0} \qquad 0.64 > r' > 0.11 \tag{2c}$$

$$\text{flux} = f_{peak}\, e^{-t/45.0} \qquad 0.11 > r' \tag{2c}$$

These almost discrete values for the X-ray flare decay slope, as well as the two-slope decay process, may be the result of fundamental flare cooling processes; eg, the slope change may come from a change in dominance from radiative to conductive cooling mechanisms.

More complete data on the flaring process for each event, such as temperature and flaring region size, are necessary before more accurate statements can be made. We are in the process of obtaining and analyzing these data.

THE X-RAY FLARE AND SHORT-WAVE FADES

There is a direct causal relationship between the solar X-ray flare and the increase in absorption of hf signals (short-wave fade, or SWF). Solar X-rays ionize various constituents in the earth's atmosphere at ~ 60–90-km altitude (the D-region) and therefore leave quantities of free electrons available to absorb energy from an hf signal propagating through the region. Increasing solar X-ray flux increases the number of free electrons, hence increasing the absorption that a signal undergoes. Higher-frequency signals are absorbed less than lower-frequency ones, because they move the electrons less (hence the likelihood of an energy-absorbing collision with a neutral particle is smaller). This means that for a given X-ray flux there is a lowest frequency below which the signal strength is less than some threshold. We shall call this frequency the lowest observable frequency (LOF). This concept has been described in detail (ref 3).

RB Rose, and others (ref 2, 1974) developed expressions for the empirical relationship between the X-ray flux and the LOF, depending on the path length of the propagating signals. Specifically, the equations for the relationships are:

long path (>1500 km)

$$\text{flux} = 0.01038\,(f_l - 15.0) - 0.003 \sin\,[0.849\,(f_l - 15.6)] \tag{3a}$$

$$\text{where } f_l = \text{LOF}\left(1 + \frac{1}{10\cos^2\chi}\right) \quad \chi = \text{zenith angle, } f_l \text{ in MHz}$$

$$\text{short path } (<1500 \text{ km}) \text{ flux} = 1.03856 \times 10^{-6}\,(\text{LOF})^4\,(\cos\chi)^{-3} \tag{3b}$$

The Rose (and others) algorithm had to invert these relationships to go from a known X-ray flux to a LOF. In our case we just put in the frequency of interest and determine at what flux value it becomes the LOF. Then, by using the previous section's models for the flare duration, we invert equation (2a-d) to determine a time of recovery for a given frequency. By stepping though frequencies, a curve of frequency vs time of recovery can be calculated (fig 2).

[3]NELC TN 3304, Lowest Observable Frequency (LOF) Model: Solrad Application, PE Argo and JR Hill, January 1977. (NELC TNs are informal publications intended chiefly for internal use)

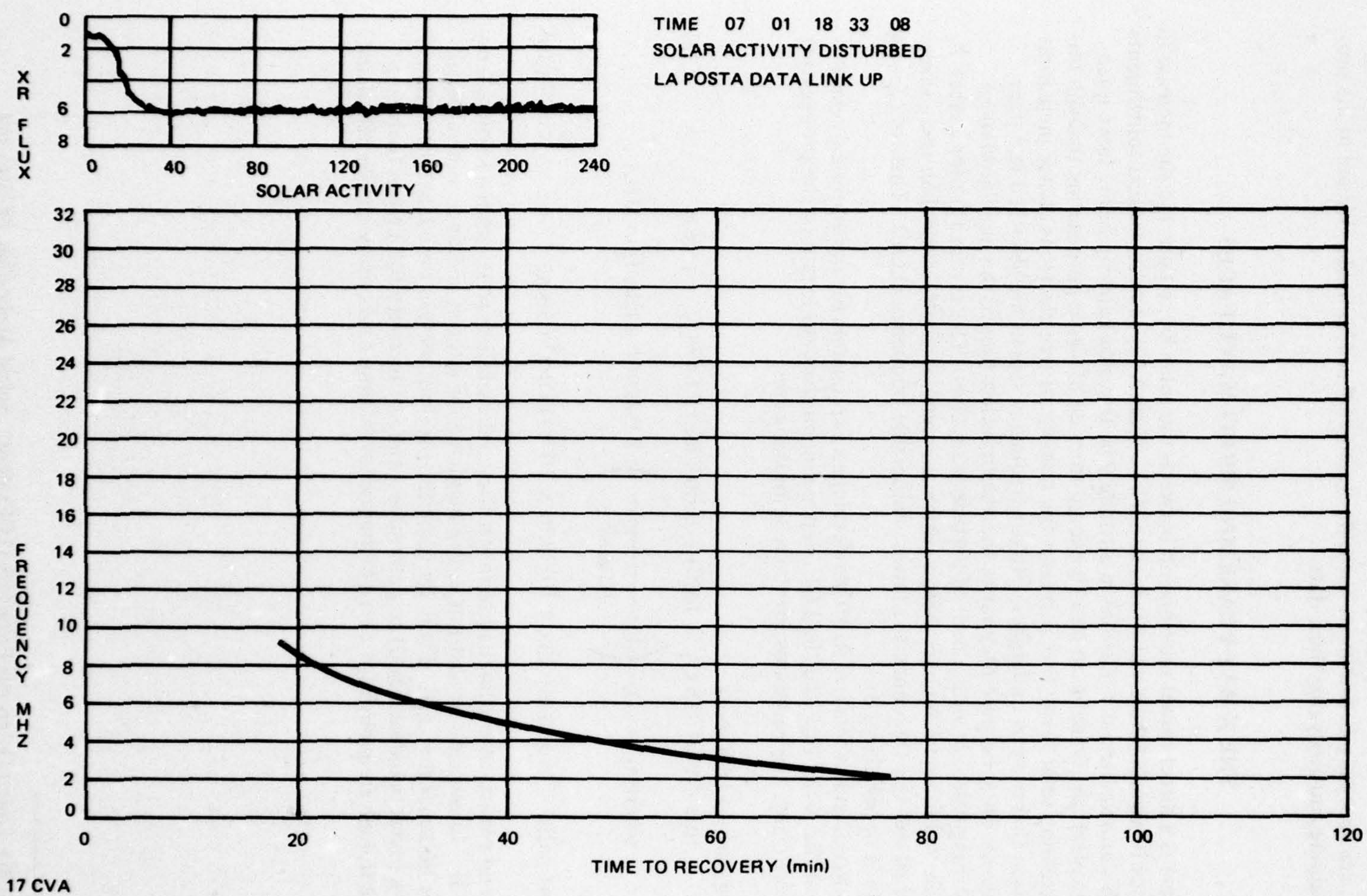

Figure 2. Frequency versus time of recovery, Solrad Prophet display.

FADE RECOVERY MODEL

The above two sections describe the concepts necessary to go from an X-ray event to a hf time-to-recovery prediction. This section will discuss in more detail some of the actualities of doing such predictions; eg, determining event start and event peak, checking for multiple bursts, monitoring prediction accuracy, and, in the event it is failing, providing an updated prediction. We will ignore details such as keeping track of data gaps, bad data, etc (we assume that the interested reader will figure out a scheme if necessary), because these are ancillary to the actual model.

Under nonflaring conditions each 1-minute averaged X-ray flux value is compared to a 60-minute running average of the X-ray flux. Along with the running average the standard deviation of the previous 60 values is computed, and if the 1-minute averaged flux remains more than two standard deviations above the running average for two samples, then an "event start" is flagged.

Because many, many small flaring variations occur, and because it nominally takes an X-ray flux of $\sim 5 \times 10^{-3}$ ergs/cm^2/s to affect the ionosphere, a threshold of 5×10^{-3} must be achieved before the event routine goes into a "flare" mode. In order to expedite the model's "start up" capabilities, an initialization procedure is used for the pre-event average. Basically, data are taken for 10 minutes and then the flare search is allowed to review incoming data, with allowance made for the small data sample, until 60 minutes of data has been taken.

In the "flare" mode the background averaging is stopped and the X-ray fluxes are put into a buffer array that is used in calculating the rise characteristics. An event peak is "declared" when a flux value is followed by two consecutive lower values. Note this is a tradeoff between rapid recognition of the event peak and a premature decision that will have to be remade. The rise time is considered to be the time between the background plus 40% of flux change and background plus 90% of flux change. This choice obviates many of the difficulties in determining the exact start and peak times, and does give good results in the modeling.

The model also monitors the flare data, searching for multiple peaks. These can be found provided either of two criteria is met: (1) the flux values begin rising again, and rise above the previous peak, or (2) the flux increases to a factor of 1.5 above a previous flux value. If either of these conditions is met, then the model begins searching for a new peak.

The model fits a least squares straight line (logarithmic) through the incoming X-ray data (during the decay of an event), and so has a real-time estimate of the actual slope. At the same time the routine is constantly comparing the actual X-ray flux to the model's predicted value. If these differ by more than a factor of 2, the routine then uses the least squares slope to determine which of the four model slopes is most suitable for use in generating an update. The routine also compares the predicted flux to an extrapolation of the least squares straight line. If these differ by more than a factor of 1.6, then an update is required. A nominal value of ratio (flux change to rise time) corresponding to the new slope is then inserted into the previous value of ratio, and the model is allowed to run again. The allowed difference in actual and predicted fluxes must be large enough not to cause continual slope changes while still small enough to keep accurate predictions available.

MODEL EVALUATION

The flare modeling routine was run on a series of X-ray events measured by Solrad 9. (These events were not used in the development of the model.) These data are read serially from a magnetic tape in a simulation of real-time data (ie, the model gets 1-minute averaged flux values). The events selected for display are intended to show both the shortcomings and strong points of the modeling routine. The vertical lines indicate that a peak (or update) has been recognized. The crosses are the predictions, the solid line represents the data.

Figure 3 shows the accuracy of the model at its best, recognizing the peak quickly and then following the flux decay down within close tolerances.

Figure 4 is an example of the updating capabilities of the model. The "peak" of the update is not the actual flux value measured but the extrapolated least squares fit. This was done to minimize the effects a large "noise" spike might have on the predictions.

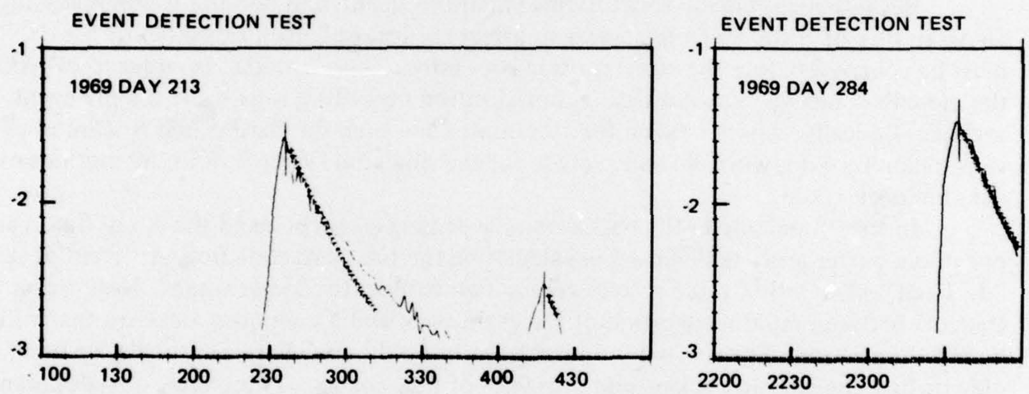

Figure 3. The X-ray event detection and decay model, operating in real time. The + symbol is the predicted decay curve; the vertical line indicates the determined peak.

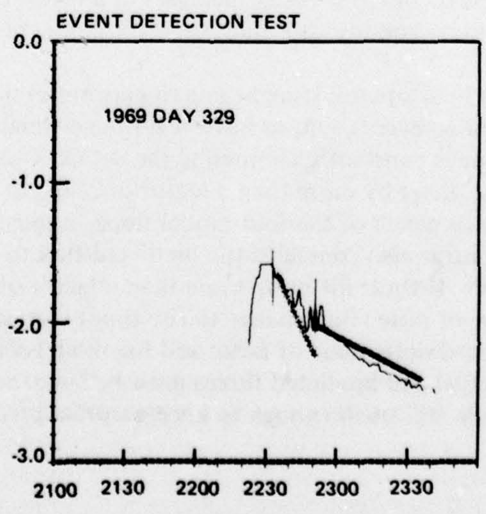

Figure 4. Similar to figure 3, but showing the updating capability. The second vertical line demarcates the time of updating.

Figure 5 is an example of a large, complex event. Note that the routine does run into some difficulties with this event. The two early, small events (between 2000 and 2100) have peaks below 5×10^{-3} ergs/cm^2/s, and so will have extremely small effects on the ionosphere. The first 45 minutes in the large event are accurately predicted. The update occurring at 2217 uses the slope from the previous 10 minutes (which is abnormally steep for this event), and so picks the steepest slope in the model for the predictions. After recognizing the error, a new update is called at ~2224. This prediction continues accurately until a new burst begins. One of the model weaknesses is in recognizing a second burst. The rapid, clean rise of this second burst makes it easy to recognize (figure 9 is an example of a more difficult case). This second burst peaked, and remained high for several minutes. Therefore, the initial prediction was off (although the slope was correct). When the update was made, the model used the flat top to calculate a slope, and so was radically in error. At 2321 an update was made, bringing predictions in line with reality. Then at 2332 another update was made, picking a "bad" slope. The problem here, as with the first update, is the fact that the slope over the previous 10 minutes was anomalous for this event.

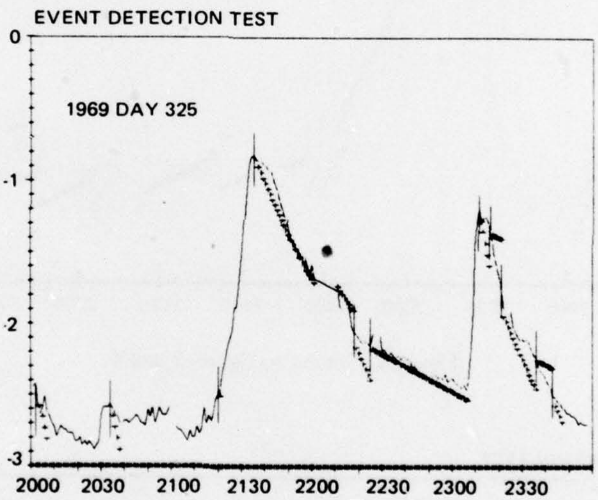

Figure 5. Similar to figures 3 and 4 (large, complex event).

The next four figures (6–9) are examples of the model's capabilities. Note that the large events are modeled very well, while the low-level events (below ~2) that occur in conjunction with the large events are not well fitted. It is difficult to get the model sensitive enough to "see" these little events during a large event, and attempts to do this have invariably made predictions on the large events deteriorate. Therefore, we have chosen to ignore these, armed with the knowledge that individual small events are well modeled (fig 3).

Notice in figure 9 that between 1445 and 1500 (as well as between 1800 and 2000) the model gave downgoing predictions while the flux level was actually rising. This is the thresholding problem in multiple bursts mentioned in the discussion of figure 4. These two events were initially slow rising, and the routine did not recognize them as beginning new events. Recognition finally occurred and in both cases the model stopped giving spurious predictions and settled down to look for a peak. Notice that both large events were accurately predicted for most of their decay.

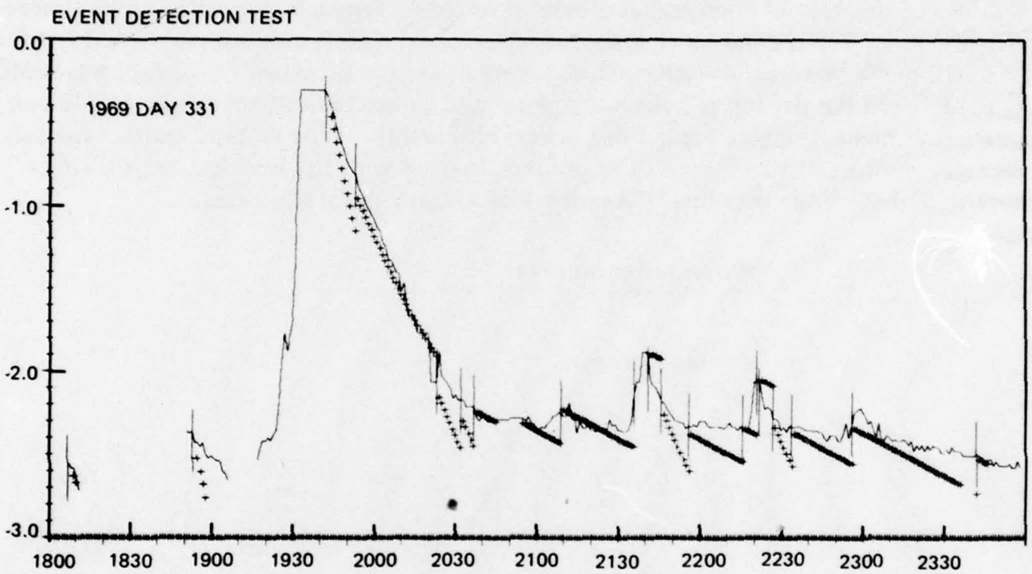

Figure 6. Similar to figures 3 and 4.

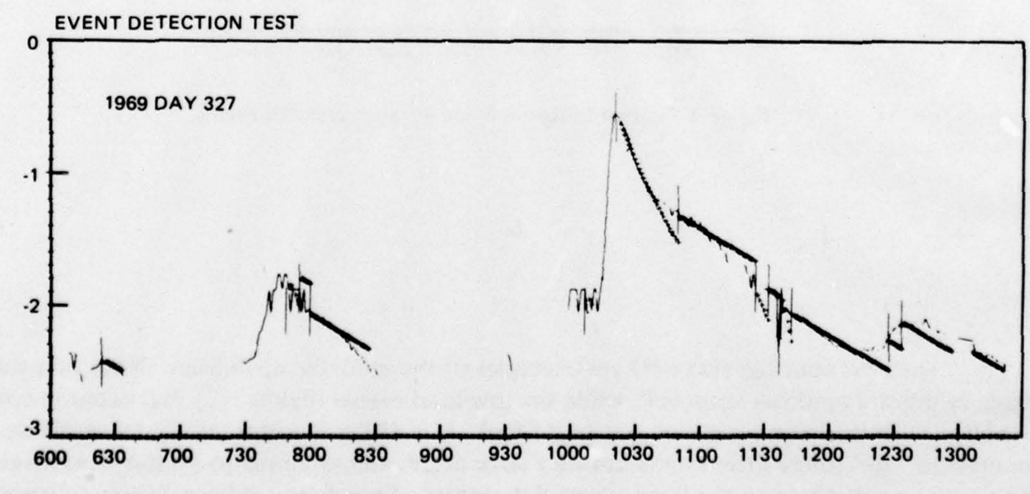

Figure 7. Similar to figures 3 and 4.

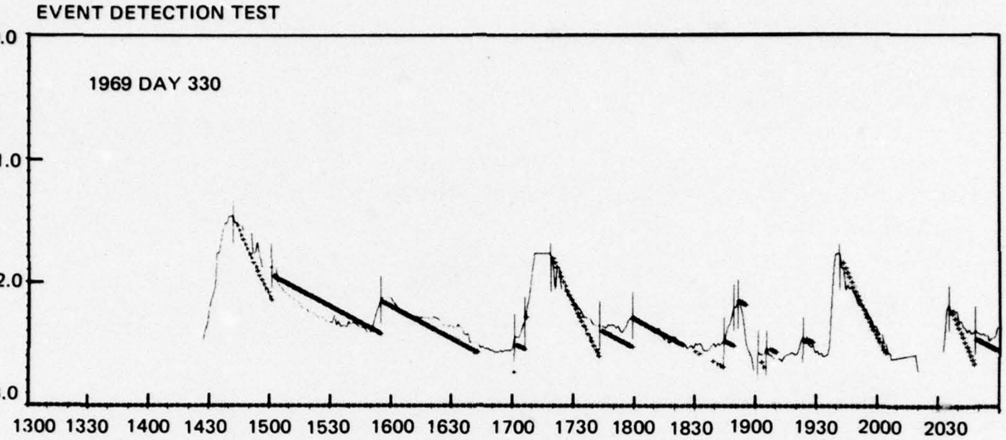

Figure 8. Similar to figures 3 and 4.

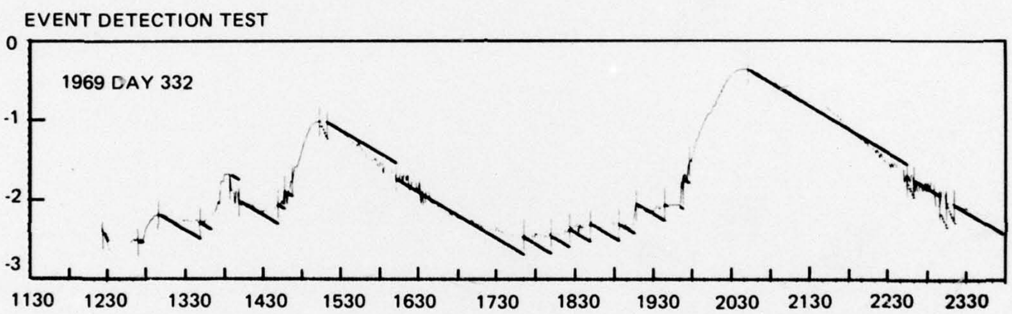

Figure 9. Similar to figures 3 and 4.

SUMMARY

We have developed a model for predicting, in real time, the time-to-recovery for hf signals during a solar X-ray event. The model is designed to give predictions as early in the event as possible, and is backed by an update scheme to correct inaccurate predictions when such are recognized. The model was made possible by the fact that the recovery period of most solar X-ray events can be characterized by an exponential decay with one of four time constants. The choice of time constant can be made by using observations of the rise portion of the event.

Several examples of the model's event-detecting capabilities, with examples of the "updating" of the predictions, are given. In modeling a "real life" phenomenon such as a solar flare there must be tradeoffs between "timeliness of prediction" and "accuracy". The "update" routine was developed to alleviate much of this problem. However, the update concept has its own similar tradeoff, inasmuch as under some circumstances it may give corrections much too often. This is important because the communications officers using such predictions would find it tiresome to be continuously getting changes, and yet they have a need for accuracy. The present model does give a good compromise, particularly in that most of the updates are made at X-ray fluxes below 10^{-2} ergs/cm^2/s (0.1–0.8-nm flux), and this is below the "major" level of significance.